Transcranial attenuation in bone conduction stimulation

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ABSTRACT

In bone conduction (BC) stimulation, the sound travels from the site of stimulation to the ipsilateral and contralateral cochlea. A frequency dependent reduction in BC hearing sensitivity occurs when sound travels to the contralateral cochlea as compared to the ipsilateral cochlea. This effect is called transcranial attenuation (TA) that is affected by several factors. Experimental and clinical studies describe TA and the factors that have an effect on it. These factors include stimulus location, coupling of a bone conduction hearing aid to the underlying tissue, and the properties of the head (such as geometry of the head, thickness of the skin and/or skull, changes due to aging, iatrogenic changes such as bone removal in mastoidectomy, and occlusion of the external auditory canal). While TA has an effect of the patient's benefit of BCHAs, there seems to be a discrepancy between experimental measurements and clinical relevance. The effects are small and the interindividual variability, in comparison, is rather large. However, a better understanding of these factors may help to determine the site of attachment, the coupling mode, and possibly the fitting of a BCHA, depending on its indication.

1. Introduction

The typical way for airborne sound to stimulate the inner ear is via air conduction (AC). Alternatively, mechanical vibrations applied to the human body can elicit a hearing impression, usually referred as bone conduction (BC) hearing pathway. Some authors differentiate different BC sound stimulations including soft tissue stimulation (Freeman et al., 2000), cartilage stimulation (Shimokura et al., 2013) from direct BC stimulation on the skull or skin covered skull bone depending on the tissue a stimulator is coupled to.

It was shown that BC activates the cochlear basilar membrane in a comparable way to AC by cancellation experiments (Bekesy, 1932; Stenfelt, 2007). Regardless of the site of stimulation, both inner ears are activated by multiple coexisting mechanisms including the following (Stenfelt and Goode, 2005): 1) sound radiation into the external auditory canal, 2) inertia of the middle ear ossicles, 3) inertia of the perilymph, 4) compression and expansion of the otic capsule, 5) sound pressure transmitted via the fluid pathways such as the cerebrospinal fluid via third windows (internal auditory canal, vestibular aqueduct). Although inertia of the perilymph and compression and expansion of the otic capsule are dominant under physiological conditions (Stenfelt, 2016), each of these BC mechanisms probably have different onset intensities and different phases, are dominating at different frequency regions, or become important in pathological situations.

Clinically, stimulation with BC hearing aids (BCHA) is helpful for patients suffering from conductive or mixed hearing loss who cannot wear conventional hearing aids (Hulecki and Small, 2011; Pfiffner et al., 2011a).

Another indication for BCHA is single-sided deafness (SSD), which is defined as severe to profound sensorineural hearing loss in one ear and normal hearing in the contralateral ear. SSD patients suffer from reduced audibility on the impaired side, reduced speech perception in the presence of background noise, and from inability or difficulty to localize sound (Akeroyd, 2006). Quality of life has been shown to be reduced (Wie et al., 2010). The aim of BCHAs in SSD is to route sound from the deaf side to the hearing side to overcome the acoustic head shadow effect and to provide better signal to noise ratios, depending on the spatial distribution of the signal and noise sources. This is referred to Contralateral Routing Of Sound (CROS). Although BCHAs provide a relief of auditory handicap, it only gives some improvement on quality of life in some patients (Kitterick et al., 2015), and seems not to be the optimal solution for all SSD patients. In particular, SSD patients that use a BCHA cannot benefit from the advantages of binaural hearing (Cox et al., 1981), including the summation effect (redundancy

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of auditory input), the squelch effect (ability of the brain to separate sound signals from spatially separated sources), and suffer from the head shadow effect. Potentially, this discrepancy comes from the inter-individual variability of the efficacy of sound propagation by BC from the BCHA to the target ear.

Transcranial attenuation (TA) (or interaural attenuation) in BC is defined as the frequency dependent reduction in BC hearing sensitivity between contralateral and ipsilateral stimulation, when stimulation position is at corresponding positions of the two sides of the skull. Generally, it is assumed that the skull is fairly symmetrical about the midline. Therefore, TA can be determined by measuring hearing threshold for ipsilateral and contralateral stimulation, or the difference of hearing threshold between the two ears from one stimulation position is calculated. Historically, TA for BC sound is important in audiometry for the determination of the required masking sound pressure levels (Hood, 1960; Studebaker, 1964). Commonly, it is assumed in clinical practice that TA is 0 dB across the audiometric frequencies (Hood, 1960). A large interindividual variability of TA of up to 40 dB exists (Nolan and Lyon, 1981; Snyder, 1973; Stenfelt, 2005; Stenfelt, 2012) that is usually not taken into consideration for treatment decisions. These interindividual differences are also described in experimental investigations measuring 3D promontory motion in cadaver heads. It has been shown that this variability increases with increasing frequencies (Dobrev et al., 2019), and that contralateral BC stimulation reveals significant attenuation for high, but not for low-frequency stimulation (Mattingly et al., 2020). Additionally, a phase delay relative to ipsilateral stimulation is described. The aim of this review is to summarize the factors affecting TA in BC to possibly improve the treatment with BCHAs.

2. Factors that influence TA in BC

TA by BC stimulation depends on several important aspects that are discussed below. These factors include stimulus location, coupling of the BCHA to the underlining tissue, and the properties of the head (such as geometry of the head, thickness of the skin and/or skull, changes due to aging, iatrogenic changes such as bone removal in mastoidectomy, and occlusion of the external auditory canal).

2.1. Stimulus location

The mastoid is the standard position for placement of a BC stimulator in audiometry. It was shown that BC sensitivity with stimulation on the mastoid (temporal bone) was approximately 2.5 dB better compared to stimulation on the conventional BAHA implant position (parietal bone), when the BCHA vibrator is placed on the skin (Stenfelt, 2012). Moreover, Ito et al. (Ito et al., 2011) showed that stimulation on the temporal region located above the zygomatic bone just anterior to the helix root resulted in lower BC thresholds than stimulation on the mastoid at 2, 3, and 4 kHz, with significant difference at 4 kHz, when the BAHA transducer was placed using a headband. This finding was confirmed by a comparison of patient and cadaver head measurements (Dobrev et al., 2016). The authors also showed that stimulation at different locations on the mastoid result in comparable hearing threshold resp. promontory motion and conclude the mastoid being a reliable stimulation position for audiometric testing.

The site of stimulation has a different effect on contralateral promontory motion. In cadaver heads, contralateral promontory motion for percutaneous stimulation depends on stimulation location with smaller promontory motion below 1 kHz when stimulation is on the mastoid compared to stimulation on the parietal bone (Eeg-Olofsson et al., 2011; Rigato et al., 2019). This indicates that stimulation location has some effect below 1 kHz, although no significant difference could be shown. Above 1 kHz, the stimulus location had no effect on contralateral promontroy motion.

It is generally agreed that stimulation closer to the cochlea is more efficient for ipsilateral stimulation (Eeg-Olofsson et al., 2011). The effect of stimulation distance from the cochlea was also investigated by Stenfelt and Goode (Stenfelt and Goode, 2005). They measured promontory motion on cadaver heads from 29 stimulation positions and found a decreased response for increasing distance between the cochlea and the stimulation position while larger vibration was measured with stimulation closer to the cochlea. TA was around -2 to -3 dB below 500Hz, around 0 dB between 500 and 1000 Hz, and then increases to 10 to 20 dB at 10 kHz. Rigato et al. (Rigato et al., 2019) measured promontory motion in cadaver heads and showed lower TA for stimulation on BAHA position (parietal bone) than for stimulation at the mastoid (temporal bone), mainly because of lower ipsilateral response. The absolute contralateral response was comparable for parietal and mastoid stimulation.

2.2. Coupling condition

The effect of skin as dampening factor on BC transmission for transcutaneous BCHA is well described. It has a negative effect on BC transmission because it dampens the stimulus as much as 20 dB, slightly more on the contralateral side and especially at higher frequencies above 1.5 kHz (Chang and Stenfelt, 2019; Hakansson et al., 1984; Hakansson et al., 1985).

In percutaneous BCHAs, the attachment type varies. An optimal coupling of the BCHA to the bone can ensure a more efficient transmission of the stimulus to the bone and ultimately to the cochlea and is therefore considered to be of interest to study the coupling influence on the vibration transmission. For example, the BAHA (Cochlear, Mölnlycke, Sweden) is attached to the skull via a 4.5mm in diameter osseointegrated screw and can be regarded as single point stimulation. The Bonebridge (MED-EL, Innsbruck, Austria) is attached with two screws to the skull bone. Additionally, the housing may be in contact with the exposed dura or sigmoid sinus, depending on the available space. Finally, the bone conduction implant (BCI) has a flat contact surface to the underlying bone. Rigato et al. investigated the effect of varying the contact to bone for the BCI on TA. They compared a flat circular contact surface with small size, a flat circular contact surface with a larger diameter, and a double point contact via screws on either side of a rigid bar by comparing elicited promontory vibration of the ipsilateral and contralateral side with a LDV. A double point contact was most effective for transmission for frequencies around 6 kHz, but somewhat lower in the mid frequency range. A smaller contact area was advantageous compared to a more extended contact area in mid and high frequencies. These trends were seen on the ipsilateral and contralateral side, however the effect was more distinct on the ipsilateral side. The TA was found to be similar for all three adaptors with values up to 20 dB at high frequencies. Therefore, the three attachments investigated seem to be equally suitable for BC stimulation for the BCI.

Regardless of the coupling (transcutaneous on steelband, transcutaneous Baha Attract, or percutaneous), a significant transcranial gain in the range of 0.5 – 4.5 dB below 200 Hz was found, mainly in the axis perpendicular to the stimulation direction. A significant TA for all motion axes was measured at mid and high frequencies. However, not all motion axis showed this behavior to the same extent (Dobrev et al., 2019). The transcranial phase delay, indicates the time difference between the motions of both cochlea, and may be relevant for directional hearing with BC stimulation. In terms of transcranial phase delay, all coupling types showed a trend for increasing phase delay with increasing frequency above 500 Hz. The trend was significant above 1.5 kHz for the steel band

and the Attract, and only above 4 kHz for the percutaneous coupling. Transcranial phase delay above 4 kHz was on average 2 cycles for all coupling types, with no significant difference between types. There was less difference in the motion composition on the contralateral side, indicating that the direction of stimulation is of minor importance for contralateral stimulation (Dobrev et al., 2019). This has been supported by observations of the full skull surface motion (Dobrev et al., 2020), where the two sides of the skull move with different spatial composition (different magnitudes of orthogonal motion components) and timing relative to each other, regardless of stimulation location.

2.3. Skull bone resonances

If the head is vibrated, resonances of the skull at certain frequencies are observed. These resonances are reported to be at 800 and 1600 Hz by based on measurements on living subjects excited by a vibrating piston (Stevens, 1951). Resonance frequencies obtained from mechanical point impedance measured on skin-penetrating titanium fixtures on seven subjects were described to be at 1000 and 1500 Hz with a standard deviation of 200 to 270 Hz (Hakansson et al., 1986). In a later study, he described between 14 to 19 resonance frequencies from 0.5 to 7.5 kHz (Hakansson et al., 1994). Intersubjective variability is large, probably due to differences in skull geometry and in mechanical parameters. These differences between subjects occur not only in the resonance frequencies itself, but also the spacing of the resonance frequencies. The dampening of the resonances is relatively high, therefore it is concluded that they do not significantly affect hearing by BC. On the other hand, antiresonances are found that would be expected to cause significant reduction in the sound transmission. However, since a reduction of transcranial sound transmission is not observed, it is assumed that sound transmission follows different pathways, i.e. through the base of the skull, or that the measured points happened to be on a nodal line (Hakansson et al., 1994). A more recent investigation of mechanical impedance of the skull (Hakansson et al., 2020) indicated a frequency dependent behavior of the skull depending on the anti-resonance. Below the anti-resonance, the motion of the skull is mass controlled and a rigid body motion is visible. Since the head is firmly attached to the torso at the level of the neck, the motion is smaller than theoretically expected without head attachment. At the resonance frequency, the compliance in the skull bone interacts with the moving mass on the contralateral side in a way such that the moving mass of the contralateral side acts in the opposite direction. Therefore, it counteracts the excitation force. At frequencies above the anti-resonance, the mass on the contralateral side is decoupled, moving less than the ipsilateral side. At the highest frequencies, the impedance is mainly mass controlled, since only the mass of the bone very close to the implant and the mass of the implant is involved.

The intersample variability of the frequency and extent of the resonances and anti-resonances could be partially explained by intersample variation in the spatial response of the vibrations of the skull, and the promontory in particular. Previous 3D measurements of the promontory in cadaver heads (Dobrev et al., 2018) have indicated that the maximum (combined) velocity vector, indicative of the total kinematic energy at the measurement point, is a better descriptor of transcranial attenuation than any individual motion component. This is because the combined motion (the maximum of the vectorial summation of all 3 orthogonal components of the velocity) exhibits less resonances and anti-resonances, also resulting in less intersample variation, than any individual motion component.

2.4. Change of skull properties with age

In pediatric audiology, limited knowledge about TA is available. TA undergoes changes during maturation of the skull. It is described that auditory brainstem response at 500 and 2000 Hz BC tone-bursts show longer wave V latency and lower amplitude for recordings made in the contralateral ear compared to the ipsilateral ear, in infants between 2 weeks to 13 months of age (Foxe and Stapells, 1993). Similar findings were described in the comparison of ipsilateral and contralateral frequency specific auditory steady state response (ASSR) measured in infants (0-11 months) (Small and Stapells, 2008). The authors combined amplitude and phase delay for a measure of asymmetry, and found a 78% occurrence of asymmetry in infants compared to 44% occurrence of asymmetry in adults. Infants also had significantly poorer thresholds for contralateral ASSR, while adults did not show significant differences between the two sides. Significantly larger TA was found in young infants, up to two years of age, compared to adults, by comparing sound pressure in the ipsilateral and contralateral external auditory canal (Mackey et al., 2018). By comparing the difference of the two sides, anatomical differences of the external auditory canal, such as differences in the cartilage, could be excluded. Different contributors are discussed to be responsible for differences between infants and adults. First of all, the skull is smaller in infants, with rapid growths at the beginning of life. Second, the material properties differ with softer bones in infants resulting in lower mechanical impedance in infants that increases with age. An age dependent difference was described for adults by Hakansson et al. (2020), who measured the point impedance of the skull in patients. A difference in compliance between patients below 60 years of age, compared to patients above 60 years of age, was reported. However, this difference was not statistically significant. It is speculated that the difference in compliance is the reason for a higher anti-resonance frequency in the older group (158 Hz vs. 135 Hz). Third, in infants, the skull plates are not fused yet and even gaps between the skull plates are physiologically present to allow skull growths. With time, the suture lines become narrower and filled with fibrous tissue. Eeg-Olofsson et al. (Eeg-Olofsson et al., 2008) investigated the effect of skull sutures on promontory motion. They found smaller promontory motion for stimulation posterior of the squamosal suture, above 1.7 kHz. The suture itself or the difference in underlying bone structure (squamous bone versus mastoid) was discussed as a possible explanation. Further studies are required to shed more light onto this matter.

2.5. Effect of mastoidectomy

Little is known of the effect of the material properties of the bone on BC. Patients undergoing mastoidectomy experience a change in the thickness and structure of the mastoid bone. It has been shown that a mastoidectomy affects sound propagation, measured as promontory motion, for stimulation close to mastoidectomy (increase of 2 - 5 dB between 0.5 – 2 kHz, decrease of 10-21 dB at 6-8 kHz). No effect of mastoidectomy on promontory motion was found when the stimulation occurred at a 2-3cm distance (BAHA location) from the mastoidectomy (Dobrev et al., 2018). It can be assumed that removing bone potentially softens the skull bone structure around the site of stimulation, thus reducing the local mechanical input impedance experienced by the BC actuator. The effect of mastoidectomy was also investigated on a whole head finite element model (Prodanovic et al., 2020), where a similar trend was reported at the mid frequencies on the ipsilateral and contralateral side, but no decrease was observed at the high frequencies, contrary to the experimental studies. The two analysis differ in several aspects and are not fully comparable. While

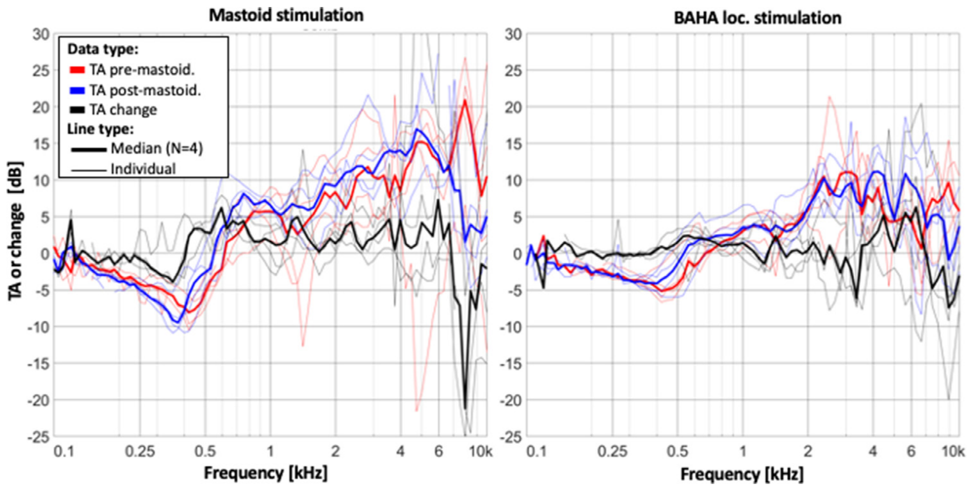

Fig. 1. Change in transcranial attenuation due to mastoidectomy, for stimulation at the mastoid (left) and the BAHA location(right), in 4 cadaver heads. Results are based on further analysis of previously published experimental data from Dobrev et al. (Dobrev et al., 2018). Red and blue lines indicate TA attenuation pre- and post-mastoidectomy, respectively, while black lines indicate the corresponding change in the TA. Thick lines are medians and thin lines are individual data. Mastoid. stands for mastoidectomy.

Dobrev et al. (2018) used the voltage to a piezo transducer as a reference, Prodanovic and Stenfelt (2020) references to the force at the stimulation site. However, since only relative changes in promontory motion are investigated, this should not be an issue, if the assumed linearity of skull bone response is assumed. Another difference is that in an experimental study, manipulations of the head are required for the laser beams to access the promontory after mastoidectomy, potentially resulting in more extensive mastectomy (removal of more bone material). Another potential difference lies in the currently incomplete understanding, and corresponding imperfect FEM representation, of mechanical behavior of the microstructure and the resulting bulk material properties of the skull under sound excitation. This could cause problems with the fidelity of the FEM results, specifically at higher frequencies. Finally, the data in the experimental study showed large (10 dB) interindividual variation at high frequencies, with both positive and negative changes, within individual results.

When it comes to TA, Prodanovic et al. (2020) showed that a mastoidectomy has almost no effect (less than 1 dB) below 2 kHz. At higher frequencies, a decrease of TA after mastoidectomy was observed 1.5 and 3 kHz, while an increase was seen above 3 kHz. These effects are within 5 dB. Qualitatively, similar behavior has been observed experimentally as well. Data from Dobrev et al. (Dobrev et al., 2018) on cadaver heads has been further processed to calculate the TA before and after mastoidectomy, for stimulation at the mastoid and the BAHA location, both with a piezo transducer attached via BI300. Median and individual data (N=4) of the results of this calculation are presented in Figure 1. Similar to the FEM, there is no measurable change at low frequencies, and an increase at mid frequencies, and a decrease at high frequencies. However, in the case of the experimental data, the change in the TA, due to the mastoidectomy, was observed already above 0.25 – 0.5kHz, at both stimulation locations. The TA shows an increase (lower transcranial transmission) in the range of 0.5-6 kHz, and a decrease (higher transcranial transmission) above 7 kHz. In addition, the experimental data shows a distinctive frequency downshift in the TA resonance at around 300-500Hz, with more pronounced frequency change for mastoid stimulation. This could be due to the weakening of the bone in the vicinity of the device, due to the mastoidectomy. A generalization of the effect of mastoidectomy is very difficult, because the pneumatization of the mastoid is variable, and the amount of bone removal during surgery differs.

2.6. Occlusion effect

Occluding the ear canal results in the sensation of increased loudness, pronounced in low frequency. It is assumed that two factors contribute to this sensation. First, occluding the external ear canal increases the contribution of ear canal sound pressure on BC hearing thresholds. In contrast, when the ear canal is open, sound radiated in the ear canal is not a dominant contributor to BC hearing. Second, the blockage of AC sound increases sound perception (Stenfelt and Reinfeldt, 2007). The occlusion effect depends on the stimulation frequency, the remaining ear canal volume, and on the site of BC stimulation. It is 10 to 15 dB less pronounced with stimulation on the mastoid as compared to stimulation at the forehead at 0.2 kHz, while there is no difference above 1 kHz (Stenfelt and Reinfeldt, 2007).

The effect of ear canal occlusion on TA was estimated on normal hearing subjects measuring ear canal sound pressure (ECSP) and hearing thresholds (Reinfeldt et al., 2013). For ECSP, they found a decreased TA of up to 5 dB in the low frequencies between 0.1 – 0.3 kHz for the occluded ear compared to the open ear. Above 1 kHz, TA increased with frequency to a similar extent for both open and closed ear canal. The hearing thresholds data showed a more pronounced difference in TA with occlusion, where the TA for the occluded ear canal was more than 5 dB lower between 0.1 and 1 kHz, compared the open ear canal. Similar to the ECSP data, the TA, based on hearing threshold data, showed little dependence on the state of the ear canal above 1 kHz. In general, occlusion of the ear canal decreases the TA at the low frequencies for the occluded ear. This effect is more pronounced when TA is evaluated by measuring hearing thresholds as compared to measuring ECSP.

3. Clinical relevance

TA can have an effect on the patient's benefit of BCHAs. In general, it can be assumed that patients with a low TA (good transcranial transmission) are good candidates for a BCHA, in the case of single sided deafness (Stenfelt, 2012). In addition, since BCHA coupling to the parietal bone results in lower TA, this stimulation site may be beneficial for patients with single sided deafness.

On the other hand, patients with a high TA are good candidates for a BCHA in case of a unilateral conductive hearing loss. In such a situation, the BCHA may be preferentially coupled to the mastoid. However, no correlation between TA at 1000 to 4000 Hz and hearing performance, measured as speech in noise, could be found in a clinical study (Snapp et al., 2016). This finding is consistent with the lack of correlation between TA and acceptance rate of a BCHA (Kompis et al., 2011). However, a more powerful output of a BCHA in high frequencies can improve speech understanding, and is therefore advantageous, especially for patients with single sided deafness.

When it comes to bilateral BCHA, little effect is measured at low frequencies. However, above 700 Hz, higher TA results in differences in spectral content and time delay in the BC sound reaching the two cochleae (Stenfelt, 2005). These differences can be used for binaural processing, but to a smaller extent compared to AC hearing.

Bilateral activation of the cochlea is relevant when it comes to the determination of BC hearing thresholds in clinical audiometry. Therefore, masking of the non-tested ear is required. Since TA depends on the previously mentioned factors such as site of stimulation, coupling, age of the patient, previous surgery such as mastoidectomy, and the state of the external auditory canal, great care is required for the realization the correct masking.

Regarding BCHA fitting, several aspects need to be taken into account. It is reasonable to assume that direct BC thresholds with the BCHA, i.e. by measurement of the patient's BC hearing thresholds through the BCHA itself, are more reliable in the correct determination of the patients' BC hearing threshold. With this approach, the large variability of the BC pathway (incl. TA) can be taken into account, by measuring the individual frequency dependence (Hakansson et al., 1984; Sadeghi et al., 2016). In particular, in patients suffering from asymmetric hearing, the measurement of the direct BC hearing thresholds is of importance to correct for individual TA for a more accurate BCHA fitting, compared to fitting based on audiometric BC threshold. This is also true for bilateral fittings (2 BCHA or 1 conventional air conduction hearing and one BCHA contralateral). However, BCHA fitting of SSD patients on the basis of direct BC thresholds does not take the acoustic head shadow effect into account. The more pronounced head shadow at high frequency ($>$ 1.5 kHz) is a defining factor for the high frequency BC hearing (Pfiffner et al., 2011b). Therefore, both the TA and the acoustic head shadow effect are clinically relevant for BCHA used as a CROS solution.

4. Avenues for future research

The interindividual differences in head size, soft tissue properties, skull geometry, skull bone thickness and microstructure make it very demanding to conduct clinical and/or experimental studies to address the different factors affecting TA in BC stimulation. Therefore, modeling analysis, such as Finite Element Models (FEM) may allow to investigate the structural differences in future. Hypothesis resulting from FEM analysis may be tested in experimental analysis on temporal bones or cadaver heads, before they be translated to clinical studies. Additionally, other measurement techniques such as intracochlear pressure measurements may bring more insights (Borgers et al. 2019; Stieger et al., 2018). This would allow to develop and test new BCHA concepts and models, before their introduction into the clinic.

Automatic scene analyzer with communication between devices in bilateral fitting (two BCHA, one CI and one BCHA, or one conventional hearing aid and one BCHA) may be beneficial. The amount of frequency dependent TA shows a large interindividual variability. This variability could be relevant in the separation of ear specific sound stimulation, at least in some situations. For example, disturbing noise could be decreased by increasing TA.

5. Conclusions

TA can have an effect of the patient's benefit of BCHAs. There seems to be a discrepancy between experimental measurements and clinical relevance. Therefore, more research is required to determine the optimal device characteristic of BCHAs, the optimal stimulation location depending on the intended side of stimulation, and coupling of the BCHA to the skull.

Author statement

Christof Röösli: Conceptualization, Methodology, Writing – Original draft preparation, Supervision, Funding aquisition. **Ivo Dobrev**: Data curation, Visualization, Writing- Reviewing and Editing. **Flurin Pfiffner:** Writing- Reviewing and Editing,

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All authors contributed by reviewing the literature, writing and editing the manuscript. All authors have read and approve of the final article.

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